



TITLE:

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CITATION:

D'Ancona, Piero ...[et al]. On the Wellposedness of the Cauchy Problem for Weakly Hyperbolic Equations of Higher Order (Microlocal Analysis and Related Topics). 数理解析研究所講究録 2002, 1261: 46-55

ISSUE DATE:

2002-05

URL:

<http://hdl.handle.net/2433/41998>

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On the Wellposedness of the Cauchy Problem for Weakly Hyperbolic Equations of Higher Order

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§1. Introduction

We consider here the Cauchy problem on $[0, T] \times \mathbf{R}_x^n$

$$(1) \quad \begin{cases} D_t^m u = \sum_{j+|\alpha|=m} c_{j,\alpha}(t) D_t^j D_x^\alpha u + \sum_{j+|\alpha|\leq d} c_{j,\alpha}(t) D_t^j D_x^\alpha u + f(t, x) \\ D_t^j u(0, x) = u_j(x) \quad (j = 0, \dots, m-1), \end{cases}$$

where $D_t = -i\partial_t$, $D_x = -i(\partial_{x_1}, \dots, \partial_{x_n})$, and $0 \leq d \leq m-1$. We shall write in short

$$p(t, \tau, \xi) = \tau^m - \sum_{j+|\alpha|=m} c_{j,\alpha}(t) \tau^j \xi^\alpha$$

for the principal part and

$$p_d(t, \tau, \xi) = \sum_{j+|\alpha|\leq d} c_{j,\alpha}(t) \tau^j \xi^\alpha$$

for the lower order terms. We shall assume that the principal part p is hyperbolic with respect to τ , that is, for any $t \in \mathbf{R}_t$, $\xi \in \mathbf{R}_\xi^n$ the roots in τ of the algebraic equation $p(t, \tau, \xi) = 0$ are all real. We name them $\lambda_j(t, \xi)$, according to the rule

$$\lambda_1(t, \xi) \geq \lambda_2(t, \xi) \geq \dots \geq \lambda_m(t, \xi),$$

thus $p(t, \tau, \xi)$ can be written

$$p(t, \tau, \xi) = \prod_{k=1}^m (\tau - \lambda_k(t, \xi)).$$

We recall that the functions $\lambda_j(t, \xi)$ are homogeneous of degree 1 in ξ .

There are many results on this problem. As to the C^∞ -wellposedness, we mention that T. Nishitani [N1] considered the case when the multiplicity of the characteristic roots is at most double. F. Colombini and N. Orrù [CO] assumed that the characteristic roots vanish of finite order at $t = 0$ and satisfy

$$t^2 \sum_{k,j=1, k \neq j}^m \frac{|\lambda'_k(t, \xi)|^2 + |\lambda'_j(t, \xi)|^2}{|\lambda_k(t, \xi) - \lambda_j(t, \xi)|^2} < \infty \quad \text{near } t = 0.$$

Moreover, K. Kajitani, S. Wakabayashi and K. Yagdjian [KWY] dealt with the case of characteristic roots vanishing of infinite order. Concerning the Gevrey-wellposedness, F. Colombini and T. Kinoshita [CK] considered the Cauchy problem in the case when the characteristic roots are Hölder continuous in t . F. Colombini, H. Ishida [CI] and H. Ishida, K. Yagdjian [IY] assumed that the characteristic roots vanish of infinite order at $t = 0$ and satisfy for some $\bar{s} > 1$

$$\frac{\Phi_1(t)^{2\bar{s}/(\bar{s}-1)}}{\phi_1(t)^2} \sum_{k,j=1, k \neq j}^m \frac{|\lambda'_k(t, \xi)|^2 + |\lambda'_j(t, \xi)|^2}{|\lambda_k(t, \xi) - \lambda_j(t, \xi)|^2} < \infty \quad \text{near } t = 0,$$

where $\Phi_1(t) = \int_0^t \phi_1 dt$ and $\phi_1(t), \dots, \phi_m(t)$ are real-valued functions such that

- (i) $\phi_k(0) = \phi'_k(0) = 0$, $\phi'_k(t) > 0$ if $t \in (0, T]$ for any $k = 1, \dots, m$.
- (ii) $\phi_1(t) \geq \phi_2(t) \geq \dots \geq \phi_m(t)$ for $t \in [0, T]$.
- (iii) $|\lambda_k(t, \xi)| \leq C_k \phi_k(t) |\xi|$ ($\exists C_k > 0$) for $k = 1, \dots, m$ and $(t, \xi) \in [0, T] \times \mathbf{R}_\xi^n \setminus 0$.
- (iv) $|\lambda_k(t, \xi) - \lambda_j(t, \xi)| \geq c \phi_k(t) |\xi|$ ($\exists c > 0$) for $k < j$ and $(t, \xi) \in [0, T] \times \mathbf{R}_\xi^n \setminus 0$.

Then they showed the wellposedness in the Gevrey classes of order $1 \leq s < \bar{s}$.

We see that in most results concerning the higher order case $m > 2$ the roots are assumed to coincide only at isolated points, and then a precise behaviour is assumed at those points. In this paper we try to give a global assumption valid in more general cases, even when this happens at an arbitrary set of points (also infinite or dense). To this end we introduce the sets Ω_σ^k , Ω_σ defined as follows: for any $0 < \sigma < 1$, $k = 1, \dots, m-1$,

$$\Omega_\sigma^k(\xi) = \{t \in [0, T] : |\lambda_k(t, \xi) - \lambda_{k+1}(t, \xi)| \leq \sigma\}$$

and

$$\Omega_\sigma(\xi) = \bigcup_{k=1}^{m-1} \Omega_\sigma^k(\xi).$$

These sets enclose, for each ξ , the points t where the roots coincide; thus we can regard the measure $\mu(\Omega_\sigma)$, which is a function of σ , ξ , as a measure of the defect of strict hyperbolicity of p . Here $\mu(A)$ is the Lebesgue measure in \mathbf{R}_t of the set $A \subseteq [0, T]$. We denote by $AC([0, T])$ the space of absolutely continuous functions on $[0, T]$ and by $G^s(\mathbf{R}^n)$ the space of Gevrey functions $g(x)$ satisfying $\sup_{x \in K} |D_x^\alpha g(x)| \leq C_K \rho_K^{|\alpha|} |\alpha|!^s$ for any compact set $K \subset \mathbf{R}^n$, $\alpha \in \mathbf{N}^n$.

Our first result is the following:

THEOREM 1. (*Gevrey-wellposedness*). Assume that the coefficients $c_{j,\alpha}(t)$ of p , p_d belong to $C^0([0, T])$ and the characteristic roots of the principal part $\lambda_1, \dots, \lambda_m$ belong to $AC([0, T])$ and that there exist constants $C > 0$, $a \geq 0$ and $b > 0$ such that for any $0 < \sigma < 1$, $|\xi| = 1$, $k = 1, \dots, m-1$

$$(2) \quad \mu(\Omega_\sigma(\xi)) \leq C\sigma^a,$$

$$(3) \quad \int_{[0, T] \setminus \Omega_\sigma^k(\xi)} \frac{|\lambda'_k(t, \xi)| + |\lambda'_{k+1}(t, \xi)|}{|\lambda_k(t, \xi) - \lambda_{k+1}(t, \xi)|} dt \leq C\sigma^{-b}.$$

Then, when the degree d of the lower order terms satisfies

$$0 \leq d \leq \frac{m(a+b)}{a+b+1},$$

the Cauchy problem (1) is wellposed in the Gevrey classes of order

$$(4) \quad 1 \leq s < 1 + \frac{a+1}{b},$$

i.e., for any data $u_j \in G^s(\mathbf{R}^n)$ and $f \in C^0([0, T]; G^s(\mathbf{R}^n))$ the Cauchy problem (1) has a unique solution $u \in C^m([0, T]; G^s(\mathbf{R}^n))$. Moreover, when the degree d of the lower order terms satisfies

$$d > \frac{m(a+b)}{a+b+1},$$

then the problem is wellposed for

$$(5) \quad 1 \leq s < \frac{m}{d + a(d-m)}.$$

Remark 1. In the cases mentioned above, when $\lambda_1(t, \xi), \dots, \lambda_m(t, \xi)$ vanish of infinite order, assumption (2) can be dropped (one is forced to choose

$a = 0$). Thus by Theorem 1 we see that the Cauchy Problem (1) is wellposed in the Gevrey classes of order

$$1 \leq s < \min \left\{ 1 + \frac{1}{b}, \frac{m}{d} \right\}.$$

Remark 2. M. D. Bronshtein [B], S. Wakabayashi [W] proved the Lipschitz (or Hölder) continuity in t of the characteristic roots of hyperbolic polynomials with smooth coefficients (see also [M]). Thus if we assume that $c_{j,\alpha}$ are smooth for $j + |\alpha| = m$, we can drop the assumption that λ_j belong to $AC([0, T])$.

Remark 3. It is well-known that the lower order terms do not influence the C^∞ -wellposedness for strictly hyperbolic equations (the multiplicity of the characteristic roots is equal to 1) and the lower order terms of order $d = m - 1$ give the Gevrey- wellposedness of order $1 \leq s < m/(m - 1)$ for weakly hyperbolic equations (the multiplicity of the characteristic roots is equal to m) (see [B], [C], [CDS], [CJS], [OT], etc.). As the parameter a in (2) becomes greater, the type of p approaches to strictly hyperbolic type. Especially, when $d = m - 1$, the second exponent in (4) is equal to $m/(m - 1 - a)$. Taking $0 \leq a < m - 1$, we can obtain an interpolation between C^∞ and the Gevrey classes of order $m/(m - 1)$.

Example A. When the characteristic roots are

$$\lambda_k(t, \xi) = kt^h \left\{ 1 + \sin^2 \left(\frac{1}{t^{h/\alpha-1}} \right) \right\} \cdot \xi$$

for some $0 < \alpha \leq 1$, $\alpha < h < \alpha/(1 - \alpha)$ and $k = 1, \dots, m$, we find that $\lambda_1, \dots, \lambda_m$ belong to $AC([0, T])$ and also $C^\alpha([0, T])$ and vanish of finite order at $t = 0$ and satisfy (2) with $a = 1/h$ and (3) with $b = 1/\alpha - 1/h$, since

$$\begin{aligned} \mu(\Omega_\sigma(\xi)) &\leq C \int_0^{C\sigma^{1/h}} dt \leq C\sigma^{1/h}, \\ \int_{[0, T] \setminus \Omega_\sigma^k(\xi)} \frac{|\lambda'_k(t, \xi)| + |\lambda'_{k+1}(t, \xi)|}{|\lambda_k(t, \xi) - \lambda_{k+1}(t, \xi)|} dt &\leq C \int_{C\sigma^{1/h}}^T \left(\frac{1}{t^{h/\alpha-1}} \right)' dt \leq C\sigma^{1/h-1/\alpha}. \end{aligned}$$

Applying Theorem 1, we get the wellposedness in the Gevrey classes of order

$$(6) \quad 1 \leq s < \frac{h}{h - \alpha} (1 + \alpha).$$

According to [CK] or [OT], if the characteristic roots belong to $C^\alpha([0, T])$, the Cauchy problem (1) is in the wellposed in the Gevrey classes of order

$$1 \leq s < 1 + \alpha.$$

For the second order polynomial $P(t, \tau, \xi) \equiv \tau^2 - A(t)\xi^2$ where $A(t) \geq 0$, if $A(t)$ belongs to $C^{2\alpha}([0, T])$, we also know the Gevrey order (7) (see [CJS], [D1] and [N2]). We remark that (6) approaches to (7) as h tends to infinity and s can be taken arbitrarily large as h tends to α (the characteristic roots oscillate more slowly). This example implies that the oscillation and the degeneracy of the characteristic roots influence on the wellposedness independently of their regularity.

Example B. [CI] and [IY] gave an example of the following kind:

$$\lambda_k(t, \xi) = \begin{cases} k \exp\left(-\frac{1}{t^h}\right) \left\{1 + \sin^2\left(\exp \frac{\gamma}{t^h}\right)\right\} \cdot \xi \\ 0 \end{cases}$$

for some $\gamma > 0$, $h > 0$ and $k = 1, \dots, m$. They proved the wellposedness in the Gevrey classes of order $1 \leq s < 1 + 1/\gamma$. Notice that $\lambda_1(t, \xi), \dots, \lambda_m(t, \xi)$ belong to $AC([0, T])$ and vanish of infinite order at $t = 0$ (see Remark 1) and satisfy (3) with $b = \gamma$;

$$\int_{[0, T] \setminus \Omega_\sigma^k(\xi)} \frac{|\lambda'_k(t, \xi)| + |\lambda'_{k+1}(t, \xi)|}{|\lambda_k(t, \xi) - \lambda_{k+1}(t, \xi)|} dt \leq C \int_{1/(\log \sigma^{-1} + C)^{1/h}}^T \left(\exp \frac{\gamma}{t^h}\right)' dt \leq C\sigma^{-\gamma}.$$

Thus we can apply Theorem 1 and we get the same Gevrey order $1 \leq s < 1 + 1/\gamma$.

Our theorems can be applied also when the vanishing order of characteristic roots is different from the order of contact between the roots. For instance, if the characteristic polynomial is

$$p(t, \tau, \xi) = \tau^2 - 2t^\alpha \tau \xi + (t^{2\alpha} - t^{2\beta})\xi^2 \quad \text{where } 0 < \alpha < \beta,$$

we easily obtain $\lambda_1(t, \xi) = (t^\alpha + t^\beta)\xi$ and $\lambda_2(t, \xi) = (t^\alpha - t^\beta)\xi$ which implies that $|\lambda_k(t, \xi)| \leq 2t^\alpha |\xi|$ ($k = 1, 2$), $|\lambda_1(t, \xi) - \lambda_2(t, \xi)| \geq 2t^\beta |\xi|$ for $(t, \xi) \in [0, T] \times \mathbf{R}_\xi$.

Since $\lambda_1(t, \xi)$ and $\lambda_2(t, \xi)$ satisfy (2) with $a = 1/\beta$ and (3) $b = 1 - \alpha/\beta$, applying Theorem 1 we have wellposedness in the Gevrey classes of order

$$1 \leq s < 1 + \frac{\beta + 1}{\beta - \alpha}.$$

In the favourable case of analytic characteristic roots, more generally from Theorem 1 we also obtain the following results:

COROLLARY 2. (*Gevrey-wellposedness*). Assume that the coefficients $c_{j,\alpha}(t)$ of p , p_d belong to $C^0([0, T])$ and the characteristic roots of the principal part $\lambda_1(t, \xi), \dots, \lambda_m(t, \xi)$ are analytic in t and vanish at $t = 0$ and that there exist constants $C > 0$, $c > 0$ and $0 < \alpha < \beta$ such that for any $(t, \xi) \in [0, T] \times \mathbb{R}_\xi^n$

$$|\lambda_k(t, \xi)| \leq Ct^\alpha |\xi| \quad \text{for } k = 1, \dots, m,$$

$$|\lambda_{k+1}(t, \xi) - \lambda_k(t, \xi)| \geq ct^\beta |\xi| \quad \text{for } k = 1, \dots, m-1.$$

Then, when the degree d of the lower order terms satisfies

$$0 \leq d \leq \frac{m(\beta - \alpha + 1)}{2\beta - \alpha + 1},$$

the Cauchy problem (1) is wellposed in the Gevrey classes of order

$$1 \leq s < 1 + \frac{\beta + 1}{\beta - \alpha}.$$

Moreover, when the degree d of the lower order terms satisfies

$$d > \frac{m(\beta - \alpha + 1)}{2\beta - \alpha + 1},$$

then the wellposedness holds for

$$1 \leq s < \frac{\beta m}{\beta d + d - m}.$$

In Corollary 2 and Examples A and B, the characteristic roots coincide only at $t = 0$ or at a finite number of points. We give a final example to emphasize that our results allow the characteristic roots to coincide at an infinite number of points.

Example C (see also Example A). When the characteristic roots are

$$\lambda_k(t, \xi) = kt^h \sin^h\left(\frac{1}{t^{h-1}}\right) \cdot \xi$$

for some even number h and $k = 1, \dots, m$, we find that $\lambda_1(t, \xi), \dots, \lambda_m(t, \xi)$ are absolutely continuous in t , more precisely Lipschitz continuous in t and vanish at $t = (\pi j)^{1/(1-h)}$ ($j = 1, 2, \dots$), they satisfy (2) with $a < 1/h$ and (3) with $b > 1 - 1/h$. Applying Theorem 1, we get the wellposedness in the Gevrey classes of order $1 \leq s < 2h/(h-1)$ (see (7)).

§2. Sketch of the proof

When $s = 1$, the Cauchy problem (1) is wellposed in the class of real analytic functions. Therefore we can suppose that $s > 1$ for the proof. By Fourier transform with respect to x , the Cauchy problem (1) turns into

$$(8) \quad \begin{cases} p(t, D_t, \xi) \hat{u} = \hat{f}(t, \xi) + p_d(t, D_t, \xi) \hat{u} \\ D_t^j \hat{u}(0, \xi) = \hat{u}_j(\xi) \quad (j = 0, \dots, m-1). \end{cases}$$

Let $0 < \sigma < 1$ and $\varphi(r)$ be a non-negative function such that $\varphi \in C_0^\infty(\mathbf{R})$, $\varphi(r) \equiv 0$ for $|r| \geq 2$ and $\varphi(r) \equiv 1$ for $|r| \leq 1$. We define

$$\begin{aligned} \omega(t, \xi) &= \sigma |\xi| \sum_{l=1}^{m-1} \varphi\left(\sigma^{-1} \left\{ \lambda_l\left(t, \frac{\xi}{|\xi|}\right) - \lambda_{l+1}\left(t, \frac{\xi}{|\xi|}\right) \right\}\right), \\ \mu_k(t, \xi) &= \lambda_k(t, \xi) + ik\omega(t, \xi) \quad \text{for } k = 1, \dots, m. \end{aligned}$$

Moreover we denote by $q(t, \tau, \xi)$ the polynomial of degree m in τ

$$q(t, \tau, \xi) = \prod_{k=1}^m (\tau - \mu_k(t, \xi)).$$

Now we set the energy density

$$E(t, \xi) = \frac{1}{2} \sum_{l=1}^m |q_l(t, D_t, \xi) \hat{u}|^2,$$

where $q_l(t, \tau, \xi)$ is the polynomial of degree $m-1$ in τ defined by

$$q_l(t, \tau, \xi) = \frac{q(t, \tau, \xi)}{\tau - \mu_l(t, \xi)} \left(= \prod_{k=1, k \neq l}^m (\tau - \mu_k(t, \xi)) \right).$$

We denote by $'$ the derivative in t . Differentiating $E(t, \xi)$ in t and dividing by $2\sqrt{E(t, \xi)}$, by (8) we have

$$\sqrt{E}' \leq C \left(\max_{1 \leq k \leq m-1} \frac{|\lambda'_k| + |\lambda'_{k+1}| + |\omega'|}{|\lambda_k - \lambda_{k+1}| + \omega} + \omega + \frac{|\xi|^d}{\prod_{k=1}^{m-1} |\lambda_k - \lambda_{k+1}| + \omega^{m-1}} \right) \sqrt{E} + |\hat{f}|.$$

Thus, Gronwall's inequality yields the estimate

$$\begin{aligned} \sqrt{E(t, \xi)} &\leq \exp \left\{ C \int_0^T \left(\max_{1 \leq k \leq m-1} \frac{|\lambda'_k| + |\lambda'_{k+1}| + |\omega'|}{|\lambda_k - \lambda_{k+1}| + \omega} + \omega + \frac{|\xi|^d}{\prod_{k=1}^{m-1} |\lambda_k - \lambda_{k+1}| + \omega^{m-1}} \right) dt \right\} \\ &\quad \times \left\{ \sqrt{E(0, \xi)} + \int_0^T |\hat{f}(t, \xi)| dt \right\}. \end{aligned}$$

We remark that there exists $C > 0$ such that for any $(t, \xi) \in [0, T] \times \mathbf{R}_\xi^n \setminus 0$

$$C^{-1}(\sigma|\xi|)^{m-1}|\xi|^{-j}|D_t^j \hat{u}| \leq \sqrt{E(t, \xi)} \leq C \sum_{j=0}^{m-1} |\xi|^{m-1-j} |D_t^j \hat{u}|.$$

LEMMA 1. *Let $b \geq 0$. Assume that $\lambda_1(t, \xi), \dots, \lambda_m(t, \xi)$ belong to $AC([0, T])$ and satisfy (3). Then there exists $C > 0$ such that for any $0 < \sigma < 1$, $|\xi| = 1$ and $k = 1, \dots, m$*

$$\int_{\Omega_\sigma^k(\xi) \cup \Omega_\sigma^{k-1}(\xi)} |\lambda'_k(t, \xi)| dt \leq \begin{cases} C & \text{if } b \geq 1 \\ C\sigma^{1-b} & \text{if } 0 \leq b < 1 \end{cases} \leq C\sigma^{1-b},$$

where $\Omega_\sigma^0(\xi) = \Omega_\sigma^m(\xi) = \phi$ and $\Omega_\sigma^k(\xi)$ for $k = 1, \dots, m-1$ are defined in §.1.

LEMMA 2. *Let $0 \leq a < m-1$. Assume that $\lambda_1, \dots, \lambda_m$ satisfy (2). Then there exists $C > 0$ such that for any $0 < \sigma < 1$, $|\xi| = 1$*

$$(21) \quad \int_{[0, T] \setminus \Omega_\sigma(\xi)} \frac{dt}{\prod_{k=1}^{m-1} |\lambda_k(t, \xi) - \lambda_{k+1}(t, \xi)|} \leq C\sigma^{a+1-m},$$

where $\Omega_\sigma(\xi)$ is defined in §.1.

Consequently, it follows that

$$\begin{aligned} \sum_{j=0}^{m-1} |\xi|^{-j} |D_t^j \hat{u}(t, \xi)| &\leq C\sigma^{1-m} \exp\{C(\sigma^{-b} + \sigma^{a+1}|\xi| + \sigma^{a+1-m}|\xi|^{d+1-m})\} \\ &\quad \times \left\{ \sum_{j=0}^{m-1} |\xi|^{-j} |\hat{u}_j| + \int_0^T |\xi|^{1-m} |\hat{f}(t, \xi)| dt \right\}. \end{aligned}$$

When

$$d \leq \frac{m(a+b)}{a+b+1},$$

the third term is smaller and this choice gives immediately

$$|\xi|^{\gamma b} + |\xi|^{1-\gamma(a+1)} + |\xi|^{\gamma(m-a-1)+d+1-m} \leq 3|\xi|^{\frac{b}{a+b+1}}.$$

Hence, there exists $\rho > 0$ such that for any $(t, \xi) \in [0, T] \times \mathbf{R}_\xi^n \setminus 0$

$$\sum_{j=0}^{m-1} |\xi|^{-j} |D_t^j \hat{u}(t, \xi)| \leq C \exp\{\rho|\xi|^{\frac{b}{a+b+1}}\} \left\{ \sum_{j=0}^{m-1} |\xi|^{\frac{m-1}{a+b+1}-j} |\hat{u}_j(\xi)| + \int_0^T |\xi|^{\frac{(1-m)(a+1)}{a+b+1}} |\hat{f}(t, \xi)| dt \right\}.$$

In virtue of Paley-Wiener theorem, $\{D_t^j u(\cdot, t) ; t \in [0, T], j = 0, \dots, m-1\}$ is bounded in the Gevrey classes of order (5). Thus, taking into account that u is a solution of (1), we find $u \in C^m([0, T]; G^s(\mathbf{R}^n))$. This concludes the proof of Theorem 1 in the case when $d \leq m(a+b)/(a+b+1)$.

On the other hand, when

$$d > \frac{m(a+b)}{a+b+1},$$

the dominant terms in

$$|\xi|^{\gamma b} + |\xi|^{1-\gamma(a+1)} + |\xi|^{\gamma(m-a-1)+d+1-m}$$

are the last two (the first one is smaller). In this case we choose

$$\gamma = \frac{m-r}{m}$$

and proceeding as above we conclude the proof of this case and we get (4).

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